TITLE OF THE INVENTION

OPTICAL AMPLIFIER AND OPTICAL AMPLIFICATION METHOD

RELATED APPLICATIONS

This is a Continuation-In-Part application of

5   International Patent Application serial No.

PCT/JP00/01660 filed on March 17, 2000 now pending.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to an optical

10   amplifier and optical amplification method of

amplifying, at once, a multiplexed signal in which a

plurality of signal light components having different

wavelengths belonging to a predetermined wavelength

band are multiplexed.

15   Related Background Art

The optical amplifier which amplifies signal light

by guiding to a waveguide doped with a fluorescent

material together with optical pumping light of such

fluorescent material is well known. Such an optical

20   amplifier is provided in a relay station in an optical

transmission system. Especially, an optical amplifier

used in a wavelength-multiplexed transmission system

for transmitting multiplexed signal light in which a

plurality of signal light components having different

25   wavelengths are multiplexed optically must amplify the

plurality of signal light components at once at an

equal gain, and also amplify the power of each of the

plurality of signal light components to a predetermined

target value and output the signal light.

For example, reference 1, K. Inoue, et al.,

5   "Tunable Gain Equalization Using a Mach-Zehnder Optical

Fiber in Multistage Fiber Amplifiers", IEEE Photonics

Technology Letters, Vol. 3, No. 8, pp. 718 - 720 (1991)

is disclosed a technique of flattening the gain of an

optical amplifier by an optical fiber using a

10 Mach-Zehnder interferometer. Reference 2, S. Kinoshita,

et al., "Large Capacity WDM Transmission Based on

Wideband Erbium-Doped Fiber Amplifiers", OSA TOPS,

Vol. 25, pp. 258 - 261 (1998) is disclosed a technique

in which an optical attenuator with a variable

15 attenuation factor is inserted between the input-side

optical amplification section and the output-side

optical amplification section of an optical amplifier

so as to maintain constant power of signal light input

to the output-side optical amplification section even

20 when the power of signal light input to the input-side

optical amplification section varies, thereby

maintaining the power of signal light output from the

optical amplifier at a predetermined target value and

simultaneously maintaining constant gain deviation of

25 the entire optical amplifier.

SUMMARY OF THE INVENTION

In the technique described in reference 1, however, for example, to keep the power of signal light output from the optical amplifier at a predetermined target value when the loss in the input-side transmission line of the optical amplifier varies due to some reason, and the power of signal light input to the optical amplifier varies, the gain of optical amplification of signal light in the optical amplifier must be changed. If the gain is changed, the wavelength dependence of gain varies. This damages the gain flatness of the optical amplifier, and the plurality of signal light components output from the optical amplifier have different powers or so-called deviation.

In the technique described in reference 2, to keep the power of signal light input to the output-side optical amplification section at a predetermined target value by the optical attenuator when the signal light input to the input-side optical amplification section has sufficiently high power, the power must be largely attenuated by the optical attenuator. As a result, the pumping efficiency lowers to degrade the noise factor.

The present invention has been made to solve the above problems, and has as its object to provide an optical amplifier and optical amplification method capable of maintaining the output signal light power

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and gain flatness without degrading the noise factor even when the input signal light power varies.

In order to achieve the above object, according to the present invention, there is provided an optical amplifier for amplifying, at once, multiplexed signal light belonging to a predetermined wavelength band, in which a plurality of signal light components having different wavelengths are multiplexed, characterized by comprising (1) one or a plurality of optical amplification sections each of which has an optical waveguide doped with a fluorescent material and amplifies the multiplexed signal light by optical pumping of the fluorescent material, (2) an optical pumping light source for supplying predetermined optical pumping light to the optical amplification section, (3) an optical filter capable of changing a gradient $dL/d\lambda$ of a loss L (dB) with respect to a wavelength λ (nm) in the predetermined wavelength band, and (4) control means for controlling an optical pumping light output from the optical pumping light source such that light power after amplification has a predetermined target value, and for adjusting a characteristic of the optical filter to adjust a final gain characteristic.

On the other hand, an optical amplification method according to the present invention is characterized by

comprising the steps of (1) guiding the multiplexed signal light to an optical waveguide doped with a fluorescent material together with predetermined optical pumping light and optically amplifying the multiplexed signal light, (2) guiding at least one of the multiplexed signal light before amplification and that after amplification to an optical filter capable of changing a gradient $dL/d\lambda$ of a loss L (dB) with respect to a wavelength λ (nm) in the predetermined wavelength band and adjusting the gradient $dL/d\lambda$ of the optical filter to reduce a wavelength-dependent gain in the optical amplification, and (3) adjusting an intensity of the optical pumping light to adjust light power after amplification to a predetermined target value.

According to the optical amplifier or optical amplification method of the present invention, even when the input signal light power to the optical amplifier varies, the output signal light power from the optical amplifier can be maintained at a predetermined target value. In addition, even when the gain of the optical amplification section has a wavelength dependence due to variation in input signal light power, the gain flatness of the entire optical amplifier can be maintained by adjusting the gradient $dL/d\lambda$ of the loss L of the optical filter with respect

to the wavelength λ.

This optical filter preferably satisfies

$L \approx a(\lambda - \lambda c) + b$

(where λc (nm) and b (dB) are constants) in the predetermined wavelength band and changes a (dB/nm) to adjust the gradient dL/dλ. Such an optical filter can easily adjust the gradient dL/dλ. When λc is set in the predetermined wavelength band, the loss L at the wavelength λc in the predetermined wavelength band always becomes constant. This enables design with an emphasis on the noise characteristic at λc.

The optical amplifier may further comprise a gain equalizer for compensating for a inherent wavelength-dependent gain of the optical amplification section. In this case, the gain equalizer equalizes the inherent wavelength-dependent gain of the optical amplification section, and the optical filter compensates for variation in input multiplexed signal light power. This makes the gain flatness of the entire optical amplifier more excellent and facilitates control/adjustment.

Preferably, the optical amplifier further comprises a wave number monitor for detecting the number of signal light components contained in the multiplexed signal light, and the control means adjusts the target value of light power after amplification in

accordance with the number of signal light components detected by the wave number monitor. Even when the power of input multiplexed signal light varies due to an increase/decrease in the number of signal light

5   components, the power of each multiplexed signal light component can be maintained constant.

The gradient $dL/d\lambda$ of the optical filter may be adjusted, e.g., 1) on the basis of the detection result from input light power detection means for detecting

10   the light power input to the optical amplification section, 2) on the basis of the detection result from gain detection means for detecting a gain of the optical amplification section, 3) on the basis of power deviation between shortest and longest wavelengths

15   detected by detecting each wavelength and power of signal light components contained in the light output from the optical amplification section, or 4) such that a level difference between ASE light levels detected by ASE light level detection means for detecting an ASE

20   light level of each of wavelengths outside two ends of the predetermined wavelength band of the light output from the optical amplification section. Each wavelength and power of signal light components contained in the light output from the optical

25   amplification section may be detected, and an ASE light level of a wavelength at a shorter wavelength than

detected shortest wavelength and at a longer wavelength than detected longest wavelength may be detected and used for adjustment. In case 3) or 4), a wavelength for which the power deviation or ASE light level is to be detected may be determined on the basis of information related to the shortest and longest wavelengths, which are sent together with the multiplexed signal light.

In addition, when a total transmittance in the predetermined wavelength band of the optical filter is adjusted to a maximum value, the loss L is preferably adjusted to be substantially constant independently of the wavelength. This enables to reduce the noise factor especially when the input multiplexed signal light power is small.

Any one of the above arrangements and methods facilitates adjustment of the gradient $dL/d\lambda$ of the optical filter and realizes the object of the present invention.

The optical filter in the optical amplifier according to the present invention preferably comprises (1) a main optical path which guides the multiplexed signal light and is divided into first to sixth regions sequentially from an upstream side, (2) a first sub optical path which is arranged close to the first and third regions of the main optical path so that optical

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coupling of propagation light occurs, is spaced apart

from the second region of the main optical path so that

optical coupling of the propagation light does not

occur, and has a region corresponding to the second

5   region of the main optical path, the region having a

length different from that of the main optical path,

(3) a second sub optical path which is arranged close

to the fourth and sixth regions of the main optical

path so that optical coupling of the propagation light

10   occurs, is spaced apart from the fifth region of the

main optical path so that optical coupling of the

propagation light does not occur, and has a region

corresponding to the fifth region of the main optical

path, the region having a length different from that of

15   the main optical path, (4) a first temperature

adjusting device arranged in at least one of the second

region of the main optical path and the region of the

first sub optical path, which corresponds to the second

region of the main optical path, and (5) a second

20   temperature adjusting device arranged in at least one

of the fifth region of the main optical path and the

region of the second sub optical path, which

corresponds to the fifth region of the main optical

path.

25   On the other hand, in the optical amplification

method according to the present invention, preferably,

an optical filter comprising (1) a main optical path
which guides the multiplexed signal light and is
divided into first to sixth regions sequentially from
an upstream side, (2) a first sub optical path which is

5   arranged close to the first and third regions of the
main optical path so that optical coupling of
propagation light occurs, is spaced apart from the
second region of the main optical path so that optical
coupling of the propagation light does not occur, and

10   has a region corresponding to the second region of the
main optical path, the region having a length different
from that of the main optical path, and (3) a second
sub optical path which is arranged close to the fourth
and sixth regions of the main optical path so that

15   optical coupling of the propagation light occurs, is
spaced apart from the fifth region of the main optical
path so that optical coupling of the propagation light
does not occur, and has a region corresponding to the
fifth region of the main optical path, the region

20   having a length different from that of the main optical
path is used, and the gain wavelength dependence
reduction step comprises adjusting at least one of a
temperature in the first sub optical path and a
temperature in a region of the main optical path, which

25   corresponds to the first sub optical path, and at least
one of a temperature in the second sub optical path and

a temperature in a region of the main optical path, which corresponds to the second sub optical path to adjust the gradient $dL/d\lambda$ of the optical filter.

Each of the first and second sub optical paths and
5   the corresponding main optical path form a Mach-Zehnder interference device. In each Mach-Zehnder interference device, when the temperature of at least one of the optical paths is adjusted, the wavelength dependence of loss in each main optical path can be adjusted. Hence,
10   this optical filter is suitable for the optical amplifier and optical amplification method according to the present invention.

The present invention will be more fully understood from the detailed description given hereinbelow
15   and the accompanying drawings, which are given by way of illustration only and are not to be considered as limiting the present invention.

Further scope of applicability of the present invention will become apparent from the detailed descrip-
20   tion given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and
25   scope of the invention will be apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic view showing the arrangement of an optical amplifier according to the first embodiment of the present invention;

5   Fig. 2 is an explanatory view of the output-side optical amplification section and optical pumping light source, and Fig. 3 is an explanatory view of the optical filter;

Figs. 4 to 6 are graphs showing loss spectra
10   obtained when a phase value $\Delta\phi$ was changed in Examples A to C of the optical filter;

Figs. 7A to 7D are views for explaining the operation of the optical amplifier according to the first embodiment;

15   Figs. 8, 9, and 10A are schematic views showing the arrangements of optical amplifiers according to the second to fourth embodiments of the present invention, respectively, and Fig. 10B is a schematic view showing the arrangement of a modification of the fourth
20   embodiment;

Fig. 11 is an explanatory view of an optical filter and spectrum monitor device in the third embodiment;

Fig. 12 is a schematic view showing the
25   arrangement of an optical amplifier according to the fifth embodiment of the present invention, and

·Figs. 13A to 13C are views for explaining its

operation;

Figs. 14A and· 14B ·are schematic views showing the

arrangements of an optical amplifier according to the

5   sixth embodiment of the present invention and its

modification, respectively, Fig. 15 is a schematic view

showing the arrangement of an optical amplifier

according to the seventh embodiment of the present

invention, and Fig. 16 is a graph which compares the

10   noise characteristic of the seventh embodiment with

that of a conventional optical amplifier;

Fig. 17 is a view for explaining the loss spectrum

of a modification of an optical filter used in the

optical amplifier according to the present invention;

15   and

Fig. 18 is a schematic view showing the

arrangement of an optical amplifier according to the

eighth embodiment of the present invention.

20   DESCRIPTION OF THE PREFERRED EMBODIMENTS

Preferred Embodiments of the present invention

will be described below in detail with reference to the

accompanying drawings.   To facilitate the

comprehension of the explanation, the same reference

25   numerals denote the same parts, where possible,

throughout the drawings, and a repeated explanation

·will be omitted.

(First Embodiment)

Fig. 1 is a schematic view of an optical amplifier according to the first embodiment. In the optical amplifier 100 according to this embodiment, an optical coupler 130, input-side optical amplification section 111, optical filter 140, and output-side optical amplification section 112 are sequentially connected in series between an optical input terminal 101 and an optical output terminal 102. The optical amplifier 100 also has optical pumping light sources 121 and 122 for supplying optical pumping light to the input-side optical amplification section 111 and output-side optical amplification section 112, respectively, and a control circuit 150 for controlling the light powers from the optical pumping light sources 121 and 122 and the loss spectrum of the optical filter 140.

The optical coupler 130 demultiplexes some components of multiplexed signal light input to the optical input terminal 101, outputs the components to the control circuit 150, and outputs the remaining components to the input-side optical amplification section 111. The input-side optical amplification section 111 receives optical pumping light from the optical pumping light source 121, optically amplifies the multiplexed signal light sent from the optical

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coupler 130 at once, and outputs the signal light. The

optical filter 140 has a loss spectrum in which the

total loss is almost constant in the wavelength band of

the multiplexed signal light, and the gradient of loss

5   with respect to the wavelength is variable in the

wavelength band. The output-side optical amplification

section 112 receives optical pumping light from the

optical pumping light source 122, optically amplifies

the multiplexed signal light sent from the optical

10   filter 140 at once, and outputs the signal light to the

optical output terminal 102.

The control circuit 150 detects the power of

multiplexed signal light demultiplexed by the optical

coupler 130. The control circuit 150 controls the

15   power of optical pumping light to be output from the

optical pumping light sources 121 and 122 on the basis

of the power of input multiplexed signal light such

that the power of output multiplexed signal light

obtains a predetermined target value. The control

20   circuit 150 also controls the loss spectrum of the

optical filter 140 on the basis of the power of input

multiplexed signal light.

Fig. 2 is an explanatory view of the input-side

optical amplification section 111 and optical pumping

25   light source 121. The input-side optical amplification

section 111 includes an amplification optical fiber 113,

optical coupler 114, and optical isolators 115 and 116. The optical coupler 114 sends optical pumping light output from the optical pumping light source 121 to the amplification optical fiber 113 and also passes signal light output from the amplification optical fiber 113. The optical isolators 115 and 116 pass light in the forward direction but do not pass light in the reverse direction.

The amplification optical fiber 113 is an optical waveguide doped with a fluorescent material that can be excited by optical pumping light output from the optical pumping light source 121. The fluorescent material to be doped is preferably a rare earth element and, more preferably, Er. Er is preferably doped because signal light in a 1.55-μm band can be optically amplified. At this time, the wavelength of optical pumping light to be output from the optical pumping light source 121 and supplied to the amplification optical fiber 113 is preferably 1.48 μm or 0.98 μm. The output-side optical amplification section 112 and optical pumping light source 122 have the same arrangement as described above.

A preferred example of the optical filter 140 will be described next. Fig. 3 is an explanatory view of the optical filter 140. This optical filter 140 is a planar lightwave circuit formed on a substrate 10 made

of, e.g., quartz, and comprises a main optical path 20, first sub optical path 21, second sub optical path 22, heater 51 serving as a first temperature adjustment means, and heater 53 serving as a second temperature

5   adjustment means.

The main optical path 20 is an optical waveguide for guiding light incident on an optical input terminal 11 at one end face of the substrate 10 to an optical output terminal 12 at the other end face of the

10   substrate 10 and causes the light to emerge therefrom. The main optical path 20 has six regions A to F.

The main optical path 20 and first sub optical path 21 are close and optically coupled to each other in the first region A and third region C, thereby

15   forming a first optical coupler 31 and second optical coupler 32. In the second region B, the optical path length of the main optical path 20 is set to be longer than that of the first sub optical path 21, so the two optical paths are spaced apart from each other. Thus,

20   the portion of the main optical path from the first region A to the third region C and the first sub optical path 21 construct an asymmetrical Mach-Zehnder interference circuit. This portion will be referred to as a first Mach-Zehnder interference circuit 41

25   hereinafter.

Similarly, the main optical path 20 and second sub

optical path 22 are close and optically coupled to each

other in the fourth region D and sixth region F,

thereby forming a third optical coupler 33 and fourth

optical coupler 34. In the fifth region E, the optical

5   path length of the main optical path 20 is set to be

shorter than that of the first sub optical path 21, so

the two optical paths are spaced apart from each other.

Thus, the portion of the main optical path from the

fourth region D to the sixth region F and the second

10   sub optical path 22 construct an asymmetrical

Mach-Zehnder interference circuit. This portion will

be referred to as a second Mach-Zehnder interference

circuit 42 hereinafter.

The heater 51 is formed on the second region B of

15   the main optical path 20. This heater 51 adjusts the

temperature of the main optical path 20 to adjust the

optical path length difference between the main optical

path 20 and the first sub optical path 21 in the first

Mach-Zehnder interference circuit 41, thereby adjusting

20   the transmission characteristic of the first

Mach-Zehnder interference circuit 41. The heater 53 is

formed on the fifth region E of the main optical path

20. This heater 53 adjusts the temperature of the main

optical path 20 to adjust the optical path length

25   difference between the main optical path 20 and the

second sub optical path 22 in the second Mach-Zehnder

interference circuit 42, thereby adjusting the transmission characteristic of the second Mach-Zehnder interference circuit 42. The heaters 51 and 53 are controlled by the control circuit 150.

5   Heaters may be provided on the second region B of the first sub optical path 21 and on the fifth region E of the second sub optical path 22 in place of the heaters 51 and 53. Alternatively, heaters may be provided on both the main optical path and the first

10   and second sub optical paths. Instead of the heaters, Peltier elements for cooling may be provided.

In this optical filter 1, a loss spectrum $L(\lambda)$ [dB] for light input to the optical input terminal 11 and output from the optical output terminal 12 through

15   the main optical path 20 depend on both a transmittance characteristic $T_1(\lambda)$ of the first Mach-Zehnder interference circuit 41 based on optical coupling between the main optical path 20 and the first sub optical path 21 by the optical couplers 31 and 32 and a

20   transmittance characteristic $T_1(\lambda)$ of the second Mach-Zehnder interferometer 42 based on optical coupling between the main optical path 20 and the second sub optical path 22 by the optical couplers 33 and 34.

25   Generally, a transmittance characteristic $T(\lambda)$ of an asymmetrical Mach-Zehnder interference circuit is

given by

$$T(\lambda) = 1 - A\sin^2\left(\frac{2\pi(\lambda - \lambda_0)}{\Delta\lambda} + \Delta\phi\right) \qquad (1)$$

where λ [nm] is the wavelength of light, A, λ_0 [nm], and

$\Delta\lambda$ [nm] are constants determined by the structural

5   parameters of the Mach-Zehnder interference circuit,

and $\Delta\phi$ is the phase value that can be set by temperature

adjustment. A loss spectrum $L(\lambda)$ of the optical filter

1 is given by

$$L(\lambda) = -10\log\{T_1(\lambda) \cdot T_2(\lambda)\} \qquad (2)$$

10   A gradient $dL(\lambda)/d\lambda$ of the loss spectrum $L(\lambda)$ of the

optical filter 1 with respect to the wavelength will be

simply referred to as a gradient $S(\lambda)$ hereinafter.

When the constants A, λ_0, and $\Delta\lambda$ of each of the

first Mach-Zehnder interference circuit 41 and second

15   Mach-Zehnder interference circuit 42 are appropriately

designed, and the phase value $\Delta\phi$ is changed by

temperature adjustment by the heaters 51 and 53 while

maintaining an almost constant loss $L(\lambda_1)$ at a

predetermined wavelength λ_1 in a predetermined

20   wavelength band, the loss $L(\lambda)$ and gradient $S(\lambda)$ in the

wavelength band can be changed. As will be described

later, the gradient $S(\lambda)$ of the optical filter 1 has

small dependence on the wavelength λ, and the linearity

of the loss $L(\lambda)$ of the optical filter 1 with respect

25   to the wavelength λ is excellent.

The present inventor prepared several types of optical filters 1 by changing the structural parameters of the Mach-Zehnder interferometers 41 and 42 and confirmed the variability of the gradient $S(\lambda)$. The

5   result will be described below.

A table below show the structural parameters in examples.

		Example A	Example B	Example C
First Mach-Zehnder Interference Circuit	A	0.60	0.85	0.60
	λ_0	1550	1550	1590
	$\Delta\lambda$	200	200	200
Second Mach-Zehnder Interference Circuit	A	0.50	0.60	0.5
	λ_0	1600	1600	1640
	$\Delta\lambda$	200	200	200

In the optical filters of all examples, the optical path lengths in the Mach-Zehnder interference

10   circuits 41 and 42 were set to $12.5\lambda_0$ and $9.5\lambda_0$ at reference temperature. Under these conditions, the heaters 51 and 53 were operated to adjust the temperatures in the second region B and fifth region E of the main optical path 20, respectively, thereby

15   changing the phase values $\Delta\phi$ of the Mach-Zehnder interference circuits 41 and 42 within the range of 0 rad to 0.595 rad such that the phase values had opposite signs and equal absolute values.

Figs. 4 to 6 are graphs showing loss spectra

20   obtained when the phase value $\Delta\phi$ was changed in the optical filters of Examples A to C.

As is apparent from Fig. 4, in Example A, the loss ranges from 2.37 to 3.01 dB, i.e., is almost constant near the central wavelength of 1,550 nm in the wavelength band of 1,535 to 1,565 nm, and the gradient $S(\lambda)$ can be set within the range of 0 to 5.05 dB/30 nm in the wavelength band. When the phase value $\Delta\phi$ is 0.595 rad, the maximum value of the deviation from a straight line passing through a point corresponding to a loss of 2.89 dB (@central wavelength: 1,550 nm) is sufficiently as small as ± 0.21 dB. Thus, it was confirmed that the gradient $S(\lambda)$ is excellent in linearity.

As is apparent from Fig. 5, in Example B, the loss ranges from 3.65 to 3.98 dB, i.e., is almost constant near the central wavelength of 1,550 nm in the wavelength band of 1,535 to 1,565 nm, and the gradient $S(\lambda)$ can be set within the range of 0 to 10 dB/30 nm in the wavelength band. When the phase value $\Delta\phi$ is 0.314 rad, the maximum value of the deviation from a straight line passing through a point corresponding to a loss of 0.87 dB (@central wavelength: 1,550 nm) is sufficiently as small as ± 0.87 dB. Thus, it was confirmed that the gradient $S(\lambda)$ is excellent in linearity.

As is apparent from Fig. 6, in Example C, the loss ranges from 2.73 to 3.01 dB, i.e., is almost constant near the central wavelength of 1,590 nm in the

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·wavelength band of 1,575 to 1,605 nm, and the gradient

$S(\lambda)$ can be set within the range of 0 to 5 dB/30 nm in

the wavelength band. When the phase value $\Delta\phi$ is 0.595

rad, the maximum value of the deviation from a straight

5   line passing through a point corresponding to a loss of

2.89 dB (@central wavelength: 1,590 nm) is sufficiently

as small as ± 0.21 dB. Thus, it was confirmed that the

gradient $S(\lambda)$ is excellent in linearity.

When the structural parameters of the Mach-Zehnder

10   interference circuits 41 and 42 are appropriately set

such that the phase value $\Delta\phi$ is set to 0 by adjusting

the temperatures in the second region B and fifth

region E of the main optical path 20 to predetermined

bias temperatures, the phase value $\Delta\phi$ can be changed

15   within the range of 0 to +0.595 rad by making the

temperatures in the second region B and fifth region E

of the main optical path 20 higher than the bias

temperatures. In addition, the phase value $\Delta\phi$ can be

changed within the range of -0.595 to 0 rad by making

20   the temperatures in the second region B and fifth

region E of the main optical path 20 lower than the

bias temperatures. When the phase value $\Delta\phi$ is changed

within the range of -0.595 to +0.595 rad, the gradient

$S(\lambda)$ can be set within the range of $\pm a$ dB/nm in a

25   predetermined wavelength band.·

When Peltier elements are used in place of the

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·heaters 51 and 53 to raise or lower the temperatures in the second region B and fifth region E of the main optical path 20, the phase value $\Delta\phi$ can be set not only to a positive value but also to a negative value. This

5 also makes it possible to change the phase value $\Delta\phi$ within the range of -0.595 to +0.595 rad.

As described above, in the optical filter 140 shown in Fig. 3, the loss spectrum for light input to the optical input terminal 11 and output from the

10 optical output terminal 12 through the main optical path 20 is determined by the transmittance characteristic of the first Mach-Zehnder interference circuit 41 based on optical coupling between the main optical path 20 and the first sub optical path 21 by

15 the optical couplers 31 and 32 and the transmittance characteristic of the second Mach-Zehnder interferometer 42 based on optical coupling between the main optical path 20 and the second sub optical path 22 by the optical couplers 33 and 34. This optical filter

20 140 is preferable because it is integrated on the substrate 10 and has a compact structure and also because of its small insertion loss.

Operation of the optical amplifier 100 according to the first embodiment will be described next, and an

25 optical amplifier control method according to the first embodiment will be described. Figs. 7A to 7D are views

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·for explaining operation of the optical amplifier 100
according to the first embodiment. As for the loss
spectrum (Fig. 7A)·of the optical filter 140, as
described above, the loss $L(\lambda_i)$ is almost constant at

5   the predetermined wavelength λ_i in the wavelength band
of signal light, and the gradient $S(\lambda)$ is variable in
the wavelength band. The gradient $S(\lambda)$ is controlled
by the control circuit 150 which monitors the input
signal light power.

10   Assume that the input signal light power has a
predetermined value, and the gain of optical
amplification of signal light by the input-side optical
amplification section 111 and output-side optical
amplification section 112 is almost constant

15   independently of the wavelength (Fig. 7B). In this
case, when the input signal light power becomes smaller
than the predetermined value, the gain of optical
amplification of signal light by the input-side optical
amplification section 111 and output-side optical

20   amplification section 112 is controlled by the control
circuit 150 and becomes large. As a consequence, the
longer the wavelength is, the smaller the gain becomes:
the gain has wavelength dependence (Fig. 7C). At this
time, however, the gradient $S(\lambda)$ of the optical filter

25   140 is controlled by the control circuit 150. The
longer the wavelength is, the smaller the loss is set.

·Hence, the wavelength dependence of gain of the
input-side optical amplification section 111 and
output-side optical amplification section 112 is
canceled by the wavelength dependence of loss of the
5   optical filter 140. As a result, the gain
characteristic of the entire optical amplifier 100
becomes almost constant independently of the wavelength,
and the gain flatness is maintained (Fig. 7D).

   As described above, in this embodiment, even when
10 the input signal light power varies, the output signal
light power can be maintained at a predetermined target
value, and the gain flatness of the entire optical
amplifier 100 can be maintained. In addition, since
the loss of the optical filter 140 is almost constant
15 at a predetermined wavelength in the wavelength band of
signal light, the noise factor does not degrade. In
this embodiment, the optical filter 140 may be located
on the output side of the output-side optical
amplification section 112.
20 (Second Embodiment)

   Fig. 8 is a schematic view showing the arrangement
of an optical amplifier 200 according to the second
embodiment of the present invention. Fig. 8 also
illustrates an optical amplifier 200A provided on the
25 input side of the optical amplifier 200. In the
optical amplifier 200 according to this embodiment, an

·optical coupler 230, input-side optical amplification

section 211, optical filter 240, and output-side

optical amplification section 212 are sequentially

connected in series between an optical input terminal

5   201 and an optical output terminal 202. The optical

amplifier 200 also has optical pumping light sources

221 and 222 for supplying optical pumping light to the

input-side optical amplification section 211 and

output-side optical amplification section 212,

10   respectively, and a control circuit 250 for controlling

the optical pumping light sources 221 and 222 and the

loss spectrum of the optical filter 240.

The arrangement of each element is the same as in

the first embodiment except the control circuit 250.

15   The control circuit 250 detects the power of input

signal light demultiplexed by the optical coupler 230,

as in the first embodiment, and also receives

information related to the power of signal light output

from the optical amplifier 200A on the input side,

20   which is transmitted from the optical amplifier 200A on

the input side. The control circuit 250 calculates the

necessary gain on the basis of the output signal light

power of the input-side optical amplifier 200A and the

input signal light power of the optical amplifier of

25   its own and controls the powers of optical pumping

light to be output from the optical pumping light

sources 221 and 222 such that the power of output
signal light has a predetermined target value. The
control circuit 250 also controls the loss spectrum of
the optical filter 240 on the basis of the necessary

5   gain.

More specifically, when the necessary gain becomes
large, the gain of optical amplification of signal
light by the input-side optical amplification section
211 and output-side optical amplification section 212

10   becomes smaller as the wavelength becomes long; the
gain has wavelength dependence. At this time, however,
the gradient $S(\lambda)$ of the optical filter 240 is
controlled by the control circuit 250 so that the
longer the wavelength is, the smaller the loss becomes.

15   Hence, the wavelength dependence of gain of the
input-side optical amplification section 211 and
output-side optical amplification section 212 is
canceled by the loss spectrum of the optical filter 240.
As a result, the gain characteristic of the entire

20   optical amplifier 200 becomes almost constant
independently of the wavelength, and the gain flatness
is maintained.

As described above, in this embodiment as well,
even when the input signal light power varies, the

25   output signal light power can be maintained at a target
value, and the gain flatness of the entire optical

amplifier 200 can be maintained.   In addition, since

the loss of the optical filter 240 is almost constant

at a predetermined·wavelength in the wavelength band of

signal light, the noise factor does not degrade.   In

5   this embodiment, the optical filter 240 may be located

on the output side of the output-side optical

amplification section 212.

(Third Embodiment)

Fig. 9 is a schematic view showing the arrangement

10   of an optical amplifier 300 according to the third

embodiment of the present invention.   In the optical

amplifier 300 according to this embodiment, an optical

coupler 331, input-side optical amplification section

311, output-side optical amplification section 312,

15   optical filter 340, and optical coupler 332 are

sequentially connected in series between an optical

input terminal 301 and an optical output terminal 302.

The optical amplifier 300 also has optical pumping

light sources 321 and 322 for supplying optical pumping

20   light to the input-side optical amplification section

311 and output-side optical amplification section 312,

respectively, and a control circuit 350 for controlling

the optical pumping light sources 321 and 322 and the

loss spectrum of the optical filter 340.

25   The arrangement of each constituent element is the

same as in the first embodiment, and a detailed

description thereof will be omitted. As characteristic
features of this embodiment, the optical coupler 332 is
arranged on the light output side to supply a
demultiplexed part of output light to the control
5   circuit 350, and the optical filter 340 is arranged on
the downstream side of the multi-stage optical
amplifiers 311 and 312.

The control circuit 350 detects the power of input
signal light demultiplexed by the optical coupler 331
10   and detects the power of output signal light
demultiplexed by the optical coupler 332. The control
circuit 350 controls the powers of optical pumping
light to be output from the optical pumping light
sources 321 and 322 such that the power of output
15   signal light has a predetermined target value. The
control circuit 350 calculates the gain on the basis of
the output signal light power and input signal light
power and controls the loss spectrum of the optical
filter 340 on the basis of the gain.

20   More specifically, when the gain becomes large,
the gain of optical amplification of signal light by
the input-side optical amplification section 311 and
output-side optical amplification section 312 becomes
smaller as the wavelength becomes long; the gain has
25   wavelength dependence. At this time, however, the
gradient $S(\lambda)$ of the optical filter 340 is controlled

by the control circuit 350 so that the longer the wavelength is, the smaller the loss becomes. Hence, the wavelength dependence of gain of the input-side optical amplification section 311 and output-side optical amplification section 312 is canceled by the loss spectrum of the optical filter 340. As a result, the gain characteristic of the entire optical amplifier 300 becomes almost constant independently of the wavelength, and the gain flatness is maintained.

As described above, in this embodiment as well, even when the input signal light power varies, the output signal light power can be maintained at a target value, and the gain flatness of the entire optical amplifier 300 can be maintained. In addition, since the loss of the optical filter 340 is almost constant at a predetermined wavelength in the wavelength band of signal light, the noise factor does not degrade. In this embodiment, the optical filter 340 may be located between the input-side optical amplification section 311 and the output-side optical amplification section 312.

(Fourth Embodiment)

Fig. 10A is a schematic view showing the arrangement of an optical amplifier 400 according to the fourth embodiment of the present invention. In the optical amplifier 400 according to this embodiment, an

31

input-side optical amplification section 411,

output-side optical amplification section 412, and

optical filter 440 are sequentially connected in series

between an optical input terminal 401 and an optical

5   output terminal 402. The optical amplifier 400 also

has optical pumping light sources 421 and 422 for

supplying optical pumping light to the input-side

optical amplification section 411 and output-side

optical amplification section 412, respectively, a

10   spectrum monitor device 460 for monitoring the powers

of signal light components with respective wavelengths,

which are output from the optical output terminal 402,

and a control circuit 450 for controlling the optical

pumping light outputs from the optical pumping light

15   sources 421 and 422 and the loss spectrum of the

optical filter 440.

As a characteristic feature of this embodiment,

the spectrum monitor device 460 is used. The

arrangements of the remaining elements are the same as

20   in the above embodiments, and a detailed description

thereof will be omitted.

Part of light output from the optical output

terminal 402 is demultiplexed and guided to the

spectrum monitor device 460, or light output from a

25   second sub optical path 22 of the optical filter 440

having the structure shown in Fig. 3 is guided to the

spectrum monitor device 460, and the guided light is demultiplexed by the spectrum monitor device 460. This spectrum monitor device 460 can be implemented by, e.g., an AWG (Arrayed-Waveguide Grating). In this case, the

5   spectrum monitor device 460 can be formed on a common substrate together with the optical filter 440 having the structure shown in Fig. 3, so the entire device can be downsized.

       The control circuit 450 controls the power of

10   output signal light component with respective wavelengths, which are demultiplexed by the spectrum monitor device 460. The control circuit 450 controls the powers of optical pumping light to be output from the optical pumping light sources 421 and 422 such that

15   the power of output signal light has a predetermined target value. The control circuit 450 also controls the loss spectrum of the optical filter 440 on the basis of any deviation between the powers of output signal light components with respective wavelengths

20   such that the deviation becomes small.

       Preferred examples of the optical filter 440 and spectrum monitor device 460 will be described. Fig. 11 is an explanatory view of the optical filter 440 and spectrum monitor device 460. The optical filter 440

25   and spectrum monitor device 460 are formed on a common substrate 10A. The optical filter 440 has the same

structure as that shown in Fig. 3. The spectrum

monitor device 460 is formed from an AWG formed on the

substrate 10A. More specifically, the spectrum monitor

device 460 has an input-side slab waveguide 61, array

5   waveguide section 62 having a plurality of channel

waveguides, output-side slab waveguide 63, and

output-side channel waveguides 64_1 to 64_N.

Light output from the second sub optical path 22

of the optical filter 440 is input to the input-side

10 slab waveguide 61. The light is demultiplexed and

output to the channel waveguides of the array waveguide

section 62. The plurality of channel waveguides of the

array waveguide section 62 have different optical path

lengths from the input-side slab waveguide 61 to the

15 output-side slab waveguide 63 and give different phases

to the light to be guided. The output-side slab

waveguide 63 receives light from each of the plurality

of channel waveguides of the array waveguide section 62

and outputs the light to each of the output-side

20 channel waveguides 64_1 to 64_N.

The light components output to the output-side

channel waveguides 64_1 to 64_N are signal light components

having respective wavelengths, which are obtained by

demultiplexing the light output from the second sub

25 optical path 22 of the optical filter 440. The control

circuit 450 detects the powers of signal light

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components having respective wavelengths, which are output to the output-side channel waveguides 64_1 to 64_n of the spectrum monitor device 460, and controls the loss gradient of the optical filter 440 such that the

5 deviation between the powers of signal light components having respective wavelengths becomes small. The control circuit 450 may control the loss gradient of the optical filter 440 such that the deviation between powers of two signal light components having respective

10 wavelengths (e.g., the maximum wavelength and minimum wavelength) in the signal light components having respective wavelengths, which are demultiplexed by the spectrum monitor device 460.

Fig. 10B shows a modification to the fourth embodiment. A difference from the fourth embodiment

15 shown in Fig. 10A is that an optical coupler 430 for demultiplexing a monitor light component in the input signal light is arranged on the optical input terminal 401 side. Monitor light contains, e.g., information

20 related to the shortest wavelength and longest wavelength in the sent multiplexed signal light. The control circuit 450 reads the pieces of information and determines the two wavelengths for which the power deviation is to be obtained.

25 As described above, in this embodiment as well, even when the input signal light power varies, the

output signal light power can be maintained at a predetermined target value, and the gain flatness of the entire optical amplifier 400 can be maintained. In addition, since the loss of the optical filter 440 is

5   almost constant at a predetermined wavelength in the wavelength band of signal light, the noise factor does not degrade. Furthermore, in this embodiment, since the loss gradient of the optical filter 440 is feedback-controlled, stable operation is possible.

10   (Fifth Embodiment)

Fig. 12 a schematic view showing the arrangement of an optical amplifier 500 according to the fifth embodiment of the present invention. In the optical amplifier 500 according to this embodiment, a gain

15   equalizer 170 is inserted between an input-side optical amplification section 111 and an optical filter 140 of the optical amplifier 100 according to the first embodiment. The gain equalizer 170 equalizes gain wavelength dependence unique to the input-side optical

20   amplification section 111 and output-side optical amplification section 112. This gain equalizer 170 can be implemented by, e.g., an optical fiber grating element having index modulation in the core of an optical fiber or an etalon filter having a Fabry-Perot

25   resonator structure.

The operation of the optical amplifier 500

according to the fifth embodiment, i.e., an optical

amplification method according to the fifth embodiment

will be described next. Figs. 13A to 13C are views for

explaining the operation of the optical amplifier 500

5   according to the fifth embodiment. Even when the input

signal light power has a predetermined value, the gain

spectrum of the input-side optical amplification

section 111 and output-side optical amplification

section 112 is not strictly constant and has a gain

10   wavelength dependence unique to the input-side optical

amplification section 111 and output-side optical

amplification section 112 (Fig. 13A). The gain

equalizer 170 has a loss spectrum having the same shape

as that of the gain spectrum of the input-side optical

15   amplification section 111 and output-side optical

amplification section 112 at this time. Hence, the

spectrum of output light is flat.

When the input signal light power has a value

smaller than the predetermined value, the gain of

20   optical amplification of signal light by the input-side

optical amplification section 111 and output-side

optical amplification section 112 is controlled by a

control circuit 150 and becomes large. Consequently,

the longer the wavelength becomes, the smaller the gain

25   becomes, so the wavelength dependence of gain changes

(Fig. 13B). At this time, however, the loss spectrum

of the optical filter 140 is controlled and set by the control circuit 150 such that the longer the wavelength is, the smaller the gain becomes.

For the light output from the input-side optical amplification section 111 and output-side optical amplification section 112, the gain wavelength dependence unique thereto is equalized by the gain equalizer 170, so the gain (dB) is adjusted to linearly change with respect to the wavelength, as shown in Fig. 13C. After that, the remaining wavelength dependence of gain is canceled by the loss spectrum of the optical filter 140. As a result, the gain characteristic of the entire optical amplifier 500 is almost constant independently of the wavelength, and its flatness is maintained.

As described above, in this embodiment as well, even when the input signal light power varies, the output signal light power can be maintained at a predetermined target value, and the gain flatness of the entire optical amplifier 500 can be maintained. Especially in this embodiment, since the gain equalizer 170 is provided in addition to the optical filter 140, the gain flatness of the entire optical amplifier 500 is excellent. In addition, since the loss of the optical filter 140 is almost constant at a predetermined wavelength in the wavelength band of

signal light, the noise factor does not degrade. In
this embodiment, one or both of the optical filter 140
and gain equalizer 170 may be located on the output
side of the output-side optical amplification section

5   112. The same effect as described above can be
obtained even when a gain equalizer is inserted in any
one of the optical amplifiers according to the second
to fourth embodiments.

(Sixth Embodiment)

10   Fig. 14A is a schematic view showing the
arrangement of an optical amplifier 300a according to
the sixth embodiment of the present invention. The
optical amplifier 300a according to this embodiment is
different from the optical amplifier 300 according to

15   the third embodiment shown in Fig. 9 only in that an
ASE light level detector 333 is arranged in place of
the optical coupler 332 at the final stage.

The ASE light level detector 333 detects the level
of spontaneous emission light (ASE light) having

20   respective wavelengths located outside the two ends of
a predetermined wavelength band of signal light output
from an optical filter 340. A control circuit 350
adjusts the loss spectrum of the optical filter 340
such that the difference in the detected ASE light

25   level between the longest wavelength side and the
shortest wavelength side is maintained at a

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·predetermined value. Use of the level difference in

ASE light advantageously facilitates control.

When monitor light having information related to

the shortest wavelength and longest wavelength in

5 multiplexed signal light is sent together with the

multiplexed signal light, monitor light demultiplexed

by an optical coupler 331 is received by the control

circuit 350 to read the pieces of information, and

wavelengths for which the ASE light levels are to be

10 detected by the ASE light level detector 333 are set to

those outside the read shortest wavelength and longest

wavelength. In this case, even when the shortest

wavelength and longest wavelength in the multiplexed

signal light are not constant, stable optical

15 amplification can be performed.

Fig. 14B is a schematic view showing the

arrangement of an optical amplifier 600 as a

modification to the sixth embodiment of the present

invention. More specifically, an optical coupler 630,

20 input-side optical amplification section 611,

output-side optical amplification section 612, optical

coupler 631, and optical filter 640 are sequentially

connected in series between an optical input terminal

601 and an optical output terminal 602. The optical

25 amplifier 600 also has optical pumping light sources

621 and 622 for supplying optical pumping light to the

input- and output-side optical amplification sections 611 and 112, respectively, and a control circuit 650 for controlling the light powers of the optical pumping light sources 621 and 622 and the loss spectrum of the

5 optical filter 640. Light demultiplexed by the optical coupler 631 is guided to a spectrum monitor device 660 and variable bandpass filter 670. The light transmitted through the variable bandpass filter 670 is detected by a light-receiving element 680. The

10 arrangements of the amplification sections 611 and 612 and the optical filter 640 are the same as in the first embodiment, and a detailed description thereof will be omitted.

In this embodiment, the wavelengths of light with

15 the shortest wavelength and light with the longest wavelength in the signal light are detected by the spectrum monitor device 660. By controlling the variable bandpass filter 670, the ASE light levels on the shorter wavelength side of the detected shortest

20 wavelength and on the longer wavelength side of the detected longest wavelength are detected by the light-receiving element 680. The control circuit 650 adjusts the loss spectrum of the optical filter 640 such that the difference in detected ASE light levels

25 between the longer wavelength side and the shorter wavelength side is maintained at a predetermined value.

·This also facilitates control.

(Seventh Embodiment)

Fig. 15 is a schematic view showing the arrangement of an optical amplifier 700 according to the seventh embodiment of the present invention. This optical amplifier 700 incorporates a DCF (Dispersion Compensating Fiber) 770.

More specifically, an optical coupler 730, input-side optical amplification section 711, optical filter 740, intermediate optical amplification section 712, gain equalizer 760, DCF 770, and output-side optical amplification section 713 are sequentially connected in series between an optical input terminal 701 and an optical output terminal 702. ·The optical amplifier 700 also has optical pumping light sources 721 to 723 for supplying optical pumping light to the input-side, intermediate, and output-side optical amplification sections 711 to 713, respectively, and a control circuit 750 for controlling the light powers of the optical pumping light sources 721 to 723 and the loss spectrum of the optical filter 740. The arrangements of the optical amplification sections 711 to 713 and optical filter 740 are the same as in the first embodiment, and a detailed description thereof will be omitted.

To confirm the noise characteristic improving

effect of the optical amplifier 700 according to this

embodiment using an optical filter capable of adjusting

the loss spectrum, the present inventor conducted

comparative experiments for a case wherein a

5   conventional variable optical attenuator for adjusting

only the total loss ratio is used as an optical filter.

In the experiments, the noise characteristic with

respect to the input level in a dynamic range of 16 dB

from -28 dbm/ch to -12 dbm/ch was measured. When the

10   variable optical attenuator is used, it is generally

difficult to cope with an input dynamic range of 16 dB.

Hence, measurement was performed by dividing the range

into two parts: -28 dbm/ch to -20 dbm/ch and -20 dbm/ch

to -12 dbm/ch, and also for a combination thereof.

15   Fig. 16 shows the measurement results. Referring

to Fig. 16, ○ indicates a noise characteristic with

respect to the input level, which was obtained when the

total range was amplified by one type of optical

amplifier using the variable optical attenuator, △

20   indicates a noise characteristic with respect to the

input level, which was obtained when the total range

was divided and amplified by two types of optical

amplifiers using the variable optical attenuator, and □

indicates a noise characteristic with respect to the

25   input level, which was obtained when the total range

was amplified by the optical amplifier according to the

seventh embodiment of the present invention.

It was confirmed that the optical amplifier according to the present invention has an effect for improving the noise characteristic at all input levels and widening the adaptable dynamic range.

A modification of the optical filter will be described next. Each of the optical filters having the loss spectra shown in Figs. 4 to 6 has an almost constant loss near the central wavelength of the use wavelength band. However, the wavelength λ_1 at which the loss becomes almost constant may be shifted to the shorter wavelength side or longer wavelength side. For an optical filter having a loss spectrum shown in Fig. 17, the wavelength λ_1 is located at the shortest wavelength in the wavelength band. The loss spectrum can be changed between and $L_0(\lambda)$ and $L_2(\lambda)$. When the power of light input to the optical filter is maximum, the loss spectrum is adjusted to $L_2(\lambda)$. When the power of input light is minimum, the loss spectrum is adjusted to $L_0(\lambda)$ at which the loss becomes constant independently of the wavelength. For intermediate power, the loss spectrum is adjusted to $L_1(\lambda)$. Thus, degradation in noise factor especially in the short wavelength region can be suppressed. When the input power is minimum, the transmittance is maximized. Hence, the noise characteristic improving effect

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becomes conspicuous especially when the power of input light is small.

(Eighth Embodiment)

5 Fig. 18 is a schematic view showing the arrangement of an optical amplifier 300b according to the eighth embodiment of the present invention. The optical amplifier 300b according to this embodiment is different from the optical amplifier 300 of the third embodiment shown in Fig. 9 in that a wave number

10 monitor 335 for detecting the number of signal light components (wave number) contained in output multiplexed signal light is arranged at the demultiplexed side of an optical coupler 332 at the final stage.

15 When the number of waves contained in input multiplexed signal light varies, the power of the input multiplexed signal light varies, though the powers of individual signal light components do not vary. For this reason, when the power of output multiplexed

20 signal light after amplification is to be simply maintained at a predetermined value, the powers of individual signal light components increase in case of a decrease in wave number, or the powers of individual signal light components decrease in case of an increase

25 in wave number, resulting in variation.

In this embodiment, the target value of power of

output multiplexed signal light is adjusted by a

control circuit 350b in proportion to the wave number

on the basis of the output from the wave number monitor

335.   Thus, even when the wave number varies, the light

5   power after the individual signal light components are

amplified can be maintained at a predetermined value.

The present invention is not limited to the above

embodiments, and various changes and modifications can

be made.   For example, the fluorescent material to

10   doped into the amplification optical fiber is not

limited to Er, and another rare earth element (e.g., Tm,

Pr, Nd, or the like) may be used.   Instead of the

amplification optical fiber, a planar optical waveguide

doped with a fluorescent material that can be excited

15   by optical pumping light may be used.   The optical

amplifier need not always be divided into the

input-side optical amplification section and

output-side optical amplification section and may have

three or more optical amplification sections.

20